Morphological control: Applications on different scales exploiting classical and statistical mechanics

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Morphological Control: Applications on Different Scales Exploiting Classical and Statistical Mechanics

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Abstract— **We introduce the concept of morphological control and report about three on-going case studies, illustrating various conceptual and technical aspects of the application of morphological control in medical and/or chemical contexts. Up to now, most implementations of morphological control take profit of classical mechanics and so does one of ours (an inflatable support system for patients with movement impairments). The two other case studies deal with processes and devices on the micrometer scale (self-assembled chemical micro-reactors and models of induced repair in radio-oncology). We use these examples to introduce the notion of embodied process control where the role taken by classical mechanics in systems on the macro-scale is adopted by statistical mechanics in case of implementations on the micrometer scale.**

***Keywords*—Morphological Computing, Tensairity, Self-Assembly, Embodied Process Control, Radio-Oncology**

I. INTRODUCTION

The goal of this paper is to describe and motivate the concept of morphological control (The term ”define” is deliberately omitted.) We illustrate the application of morphological control by reporting about three, partially ongoing, case studies and illustrate how lessons learnt from robotics are exploited in the field of medicine and chemical process management. We don't give a detailed account of the case studies as such (see the references) nor are we ready to present a unified methodology for programming morphological control, but the presented examples highlight common features of otherwise very different systems and problem settings.

II. MORPHOLOGICAL COMPUTATION AND CONTROL

Robots and biological systems are not only controlled by their CPU's or brains, but their dynamics is determined and controlled as well by the morphology of their bodies (whereby we understand by the term "morphology" the combination of shape and material properties such as elasticity characteristics, friction coefficients etc.). For a review, see [1].

In a workshop lead by Norman Packard at the first International Conference on Morphological Computation, an attempt towards a definition of the term "morphological computation" was made. Thereby, a process was called a morphological computation if

1. It converts a reproducible input into a reproducible output.
2. It is programmable in the sense that the map between input and output is parameterized in such a way that a wide variety of outputs can be produced.
3. The process has a sort of teleological embedding.

The first requirement rules out systems that are highly susceptible towards changes of the initial conditions and the third aims at avoiding discussions (at least this is the impression of R.M.F.) whether or not a natural river flowing down a hill is solving the Navier-Stokes equations.

In what follows, we use the term "morphological control", emphasizing a distinction between control and computation: A computation maps an input onto an output, whereby the input is completely given at the start of the process. The aim of control, however, is to generate a stream of output signals, which determine reactions in a stream of input signals, the latter not completely known at the start of the computation.

The conventional notion of control is summarized in Fig. 1. Thereby, a robot gets information from the environment via some sensory system, these signals are transformed into a binary representation which in turn is processed by a conventional computer. The result of this computation is used for determining the action of the robot. In order to keep this computation as simple and reliable as possible, the influence of the robot's morphology ("physical noise") is minimized and the numbers of degrees of freedom are kept as low as possible. From a physical point of view, this is one of the reasons why most robots are heavy and stiff; measuring a limited number of system parameters then allows determining with sufficient accuracy and completeness the state (e.g. posture and velocities) of the device.

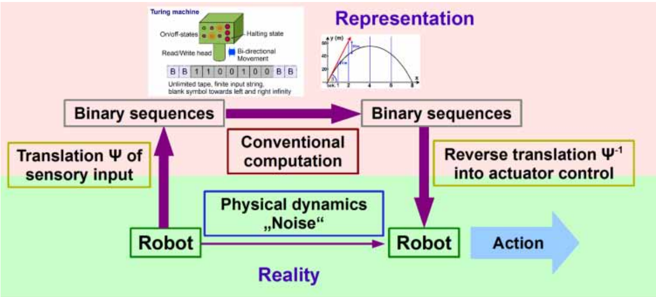

Figure 1: Conventional control attempts to reduce the influence of the robot's morphology.

Morphological control pursues a complementary strategy, described by Fig. 2. As shown in [2], taking profit of the system's morphology still allows performing arbitrary complex computations with only a minimal amount of conventional control but by exploiting the dynamics of the system itself for control tasks. The representation of the robot's state needs not anymore to be complete which in consequence enables the use of soft structures (mathematically expressed, "soft" or "elastic" means many degrees of freedom).

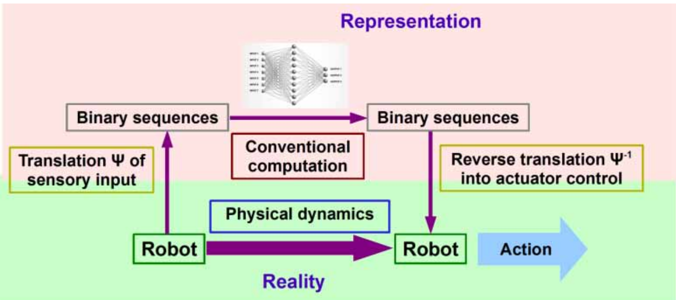

Figure 2: Morphological control exploits as much of the physical dynamics of the system as possible. The representation necessary for conventional computation does not necessarily completely reflect the robot's state.

In case of a system governed by classical mechanics, one way to achieve morphological programmability is to construct a dynamical system with a parameterized attractor landscape. A, possibly digital, control element is assumed to be able of moving the system from one basin of attraction into another one, but not to coordinate the details of a movement pattern. The pattern itself is realized and stabilized by the attractor. The parameterization of the attractor landscape leads to a certain amount of programmability.

Importantly, this form of programmability doesn't require the programmer to encode the physics of the system (as it would be necessary for a controller simulating Newton's laws), but only to know (and this even only roughly) the arrangement of the basins of attraction. The downside of such a program is that its portability is limited: it only works for a given physical system.

Why exploiting physics and chemistry for control? We claim that there are at least five reasons to do so:

1. Nature is not susceptible towards the problems of numerical analysis. This is not only true for the dynamics as such, but also for the boundary conditions. Representing extended objects and calculating e.g. their collision is numerically difficult.
2. Nature is inherently parallel.
3. In a morphological computation, the physics is already there. One can't go beyond physics, but as a benefit, one hasn't to encode physics.
4. High quality random numbers are for free (by thermal fluctuations).
5. Morphological control devices are proven to be evolvable. Evolutionary programming strategies are a promising method.

We want to illustrate what we understand by a morphological control program by another example, taken form chemistry: It is beyond present technological means to control the cooking of a potato soup by getting instructions via a simulation (including all the complex chemistry and convection of highly viscous fluids near phase transitions). However, a recipe for a potato soup needs a single page provided one works with loosely standardized pots, potatoes, ovens and spices. The recipe qualifies as a program, but a program which relies on the embodiment of the cooking process.

Programming a conventional control device requires writing a syntactically correct string of semantically meaningful functions. In contrast, programming morphological control (presently) most often means tuning parameters. Developing a methodology for identifying functional primitives and methods to combine them is one of the challenges to be mastered in the future.

III. Case Studies

A. Tensairity-based support systems for patients with movement impairments.

A side effect of aging is the gradual loss of control over complex movement patterns. This loss may have many causes, one of them can be found in the decrease of sensory and neural performance. Taking the lessons from morphological computation into account, another possible explanation for this loss becomes apparent: Aging changes the mechanical properties of the body and therefore alters, if one regards the body as a dynamical system, its attractor landscape. This attractor landscape plays a central role in morphological computation, and consequently, a change in this landscape may well reduce the body's ability to contribute to control tasks.

Viewed from this perspective, elderly people sometimes have troubles to control their movements not (at least not only) because their brains are subject to decreased performance, but because the tasks their brains have to solve increase in difficulty due to reduced support from morphological control [3], [4]. Using a novel technology, tensairity [5] we try to "reshape" the body's attractor landscape with the goal to regain morpho-computational power.

The term "Tensairity" indicates a combination of the concept of tensegrity with air; inflatable elements play a crucial role. Using pressures of only 300 mbar, inflatable bridges have been constructed, able of carrying the load of car. Recently, actuated tensairity structures have been demonstrated [6]. Inflatable structures offer various benefits in therapeutic contexts (low weight and cost, high intrinsic safety) and are highly adaptable, but caused by their softness, cannot be programmed the same way as, say, an exoskeleton.

B. *Programmable Self-Assembling Spatially Heterogeneous Micro-Reactors*

Complex chemical synthesis, such as e.g. that of branched sugars suffers from low yield if performed in a one-pot reactor. In the context of the EU-project MATCHIT, we were able to demonstrate [7] *in silico* that spatially heterogeneous reaction environments constructed from micrometer – sized reaction vessels of various types allow an increase of yield by orders of magnitude. Thereby, these vessels are equipped with linker elements of high specifity and are subject to self-assembly on a two – dimensional substrate (see Fig. 3). Besides increased yield, this miniaturization offers various novel applications. We regard such reactors as an instance of morphological computation because it is the spatial arrangement of the reaction vessels which directs the overall reaction. Control, which in the laboratory has to be exerted externally, is delegated to the morphology of the reactor. Moreover, this is done in a programmable way: We used a limited set of types of reaction vessels, each type performing a specific reaction (a reaction primitive). The order of the reaction steps was controlled by the arrangement of the vessels, which in turn was dictated by the linkers the reaction vessels were decorated with. These linkers can be chosen (rather) freely, and in consequence, a rich set of synthesis protocols can be realized.

C. *Multi-scale approaches in oncology, systems medicine*

More and more, the importance of a systemic view point becomes apparent in applied oncology. Successful therapeutic strategies combine the molecular perspective with approaches that rely on the dynamics of cellular structures on larger size- and time-scales or the various hierarchical layers of whole tissues. It is no new insight that tumors are highly adaptive and "behave" as a whole supra-cellular entity. But that the underlying mechanisms are not only coded and controlled by molecular processes is a less widespread idea. Understanding the (evolved) control of tumors on a more abstract level and may guide the development of more versatile strategies against them [8].

D. *Embodied Process Control*

The latter two examples ask for an inclusion of stochastic processes, ranging from statistical mechanics to notions of network theory in the framework of morphological computation. A thorough discussion of similarities and differences of design principles and concepts for morphological computation in stochastic and deterministic settings is in our opinion a main challenge for the future. An important step is thereby the identification of a method for choosing a suitable set of functional primitives, as discussed by [7] in the specific case for the choice of reaction primitives for glycosynthesis.

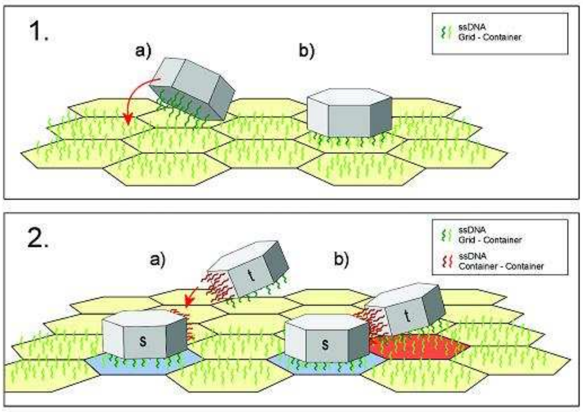

Figure 3: Self-assembly of the 2D grid of containers via specific linker molecules (ssDNA). The upper part (1) shows the association of a container to the grid, (2) illustrates the specific association between two containers (s, t) that leads to a nonrandom arrangement of the containers on the grid.

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